



**Proxemy Research
Grant NAG-I0530
Closeout Report**

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Proposal Title: Quantitative Studies in Planetary Volcanism
(Grant No. NAG-I0530)

Submitted to: Dr. Stephen Saunders
Code SR
NASA Headquarters

July 31, 2004

PROPOSAL TITLE:: Quantitative Studies in Planetary Geology

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1. Introduction

Proxemy Research had a grant from NASA to perform science research of quantitative studies of planetary volcanism. **This grant (NAG-10530) closed on April 30, 2004.** Here we summarize the scientific progress and accomplishments of this grant. Scientific publications and abstracts of presentations are indicated in the final section.

This was a very productive grant and the progress that was made in each year is summarized below. The Full Proposal originally identified four topical areas related to geologic features associated with planetary volcanism. The problems presented in the full proposal were selected because of their significance to planetary geology and our ability to make a unique contribution.

The specific topical areas were: 1) Lava flow modeling and analysis, 2) The emplacement of pahoehoe flows, 3) Mass flows on Mars and terrestrial analogs, and 4) Lava flows and bright deposits on Io. Each of the topics is discussed below. A composite list of all scientific publications and most of the related abstracts appears in Section 6.

2. Lava flow modeling and analysis

Primary Publications: Baloga, SM, PJ Mouginis-Mark, and LS Glaze, 2003, "The rheology of a long lava flow at Pavonis Mons", JGR/Planets (108, E7,5066, doi 10:1029/2002JE001981);LS Glaze, SM Baloga, and ER Stofan, 2003, "A methodology for constraining lava flow rheologies with MOLA", Icarus (doi:10.1016/A0019-1035(03)00171-4)10.1029/2002GL014757;SM Baloga, LS Glaze, MN Peitersen, and JA Crisp, 2001, "The influence of volatile loss on the thickness and density profiles of active basaltic flow lobes", JGR, 106, B7 13,395-13,405

The influence of degassing and channel formation in planetary flows. We have recently published a model for lava flows on Mars that explicitly considers the loss of volatiles while a flow is actively constructing levees [Baloga et al., 2003]. Our approach was based on [Baloga et al.2001,"The influence of degassing on thickness and density profiles in active basalt flow lobes"] that appeared in JGR Solid Earth.. We have applied the density change theory to almost two dozen lava flows on Mars and the Moon for which we have thickness information from either Viking, MOLA, or the Apollo images. It is also well-known that levee-building and other similar types of lava volume and mass loss while a flow is active has a significant effect on estimates of viscosity, lengths of flows, and advance rates. We have recently combined both of these models to obtain a new set of equations to describe a mass loss to stationary margins concurrent with a density change along the path of the flow. We have shown that the nature of the viscosity change along the flow path

has a major influence on the shape of the profile when density change and levee building are included. These profiles can be readily compared to planetary data for lava flows on Mars and the Moon. This confirmed our suspicions that the formation of stationary margins, combined with a density change along the flow path, has a dramatic effect on the thickness profile.

Lava density changes during emplacement. We developed a model for lava flow with density and rheology changes during emplacement. This manuscript was published in the Journal of Geophysical Research [Baloga et al., 2001]. In that work, we used detailed studies of the Mauna Loa 1984 flow and we considered two endmember form for the volume flowrate. We have applied the density change theory to a number of lava flows on Mars and the Moon for which we have thickness information from either Viking, MOLA, or the Apollo images. The results were based on data presented in Mouginis-Mark and Tatsumura Yoshioka (Elysium, [1998]), Zimbelman (Ascræus, [1985] and Imbrium [pers com]), Schneeberger and Pieri (Alba, [1991]), Baloga et al. (Mauna Loa, [2000]), Glaze and Baloga (Puu Oo, [1998]). Many of the most interesting planetary flows show significant channelization. Systematic dimensional data is readily available for some flows. The loss of lava volume from an active flow was treated in Baloga et al., [1998] and applications to planetary flows appears in Glaze and Baloga [1998].

Subsequently we combined both of these models to obtain a new set of equations to describe a mass loss to stationary margins concurrent with a density change. We have also investigated a linear viscosity increase and it is clear that the nature of the viscosity change along the flow path has a major influence on the shape of the profile when density change and levee building are included. These profiles can be readily compared to planetary data for lava flows on Mars and the Moon. This preliminary study confirmed our suspicions that the formation of stationary margins, combined with a density change along the flow path, has a dramatic effect on the thickness profile. These processes can almost completely mask a 1000-fold increase in viscosity.

3. The emplacement of pahoehoe flows

Primary Publications: Baloga, SM and LS Glaze, 2003, "Pahoehoe transport as a correlated random walk", JGR Solid Earth 108: 10.1029/2001JB001739; B. C. Bruno, S. A. Fagents, T. Thordarson, S. M. Baloga and E. Pilger, 2004, Non-Random Processes Control Clustering within Rootless Cone Groups on Iceland and Mars

The random walk model for pahoehoe lavas. Our approach to modeling the emplacement of pahoehoe has been to treat lava transport as a random walk. Initially, we considered simple uncorrelated random walks. Our results for small lobes of toes were conceptually very encouraging. When we scaled up the theory to flow fields and lobes of hundreds or thousands of parcels, we found that no form of correlated random walk could reproduce the shape of isolated Hawaiian lobe transects. Consequently, we invoked a very challenging form of a correlated random walk. Here the correlation is thought to come from the momentum of lava parcels in motion and a "chain of memory" connection with vent conditions. There was no useful information in the literature for this

type of random walk, but we were able to obtain a new solution that gives pahoehoe lobes transects that agree with field observations. The mathematical formalism of this new correlated random walk has been completed and the predictions have been compared with approximately a dozen transects of lobes in Hawaii. (See abstract in final section.)

Modeling pahoehoe lava. We made significant progress developing a stochastic model that explicitly incorporates random effects. The main results of this difficult problem and approach appeared in Baloga and Glaze [2003]. We statistically characterized the dimensions of pahoehoe toes [Crown and Baloga, 1999] and we have collected other field data intended to distinguish the different types of random walks. Recently, we investigated models for uncorrelated random walks, with and without bias, and spatially-correlated random walks [Baloga and Glaze, 2000]. We presently believe that pre-existing large scale topographic slope can be expressed as a "bias" in the random walk. On the basis of preliminary field observations, we have obtained broad qualitative agreement between predicted and observed shapes of isolated lobate deposits emplaced in the toe regime.

The uncorrelated random walk describes a number of qualitative features observed in the field, such as the meandering of isolated filaments and the budding of toes in the upslope direction [Baloga and Glaze, 2003]. Figure 1.1 shows the resulting cross-sections of such a flow at different time steps. The flow spreads and gently thins as it advances. A discrete binning of these curves can be compared to field data.

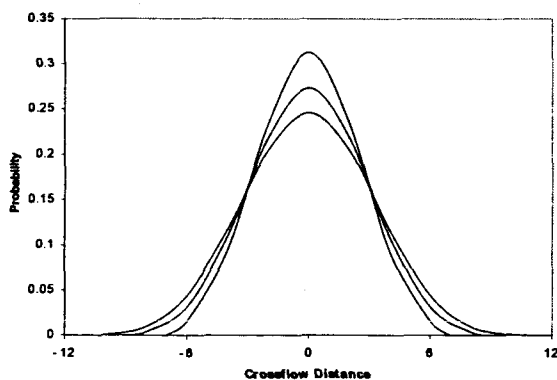


Figure 1.1 Cross-section of flow at time steps $N = 6, 8, \& 10$ (top, middle, bottom).

We were initially encouraged by the applicability of the uncorrelated random walk for large numbers of parcels. However, a number of issues arose. First, this classical random walk minimizes the interaction between parcels during transport. Thus, the limited influence of neighboring parcels precludes conventional fluid dynamic influences throughout the active lobe. In effect, we would have to abandon conventional viscous fluid dynamics except for a parcel-by-parcel application at the margin and front of the lobe. A second problem with the uncorrelated random walk became evident from computer simulations of many uncorrelated

random walks. These simulations superimposed many monofilaments. They reproduced broad, amorphous flow fields of many thousands of parcels, but were far too diffuse to represent solitary or multiple lobes. Finally, we had collected thickness transects across a dozen or so small isolated lobes at Mauna Ulu and Hualalai (e.g., Figure 1.2). On the basis of this exploratory study, it was ambiguous, at best, whether such profiles actually fit the theoretical predictions.

We addressed these issues by considering a correlated random walk and by the collection of additional field data. With a correlated random walk, some "memory" of what happened to a parcel

at prior steps is retained. Correlation is a manifestation of the momentum of the flow, inertial effects, and fluid dynamic pressure, when there are many contiguous parcels in a flow lobe.

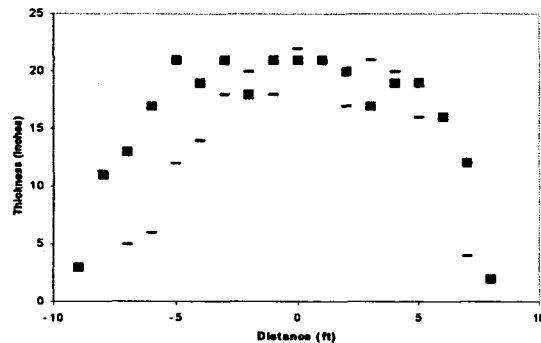


Figure 1.2 Measured pahoehoe lobe transects

In broad amorphous fields of toes, there is often a clear loss of connection between the source of lava supply and the formation of toes. As a toe forms in one location, other toes can be simultaneously budding and forming, at random, at other locations. This does indeed suggest a lack of correlation. However, in lobes, sheets, and channelized flows, there is a definite, overall flow and forcing of parcels that is the direct result of continued lava supply and fluid dynamic effects.

The development of the correlated random walk model proved to be an unexpectedly difficult challenge. We were not able to directly use any of the correlated random walks that have appeared in the literature or any of several initial attempts we developed.

4. Mass flows on Mars and terrestrial analogs

Primary Publications: Baloga SM, PJ Mouginis-Mark, and SA Fagents, 2004, "The formation of Martian rampart craters" (Submitted to JGR Planets); Mouginis-Mark, PJ, H Garbeil, JM Boyce, CSE Ui, and SM Baloga, 2004, "Geometry of Martian Impact Craters: First results from an interactive software package", JGR Planets (accepted); Barnouin-Ja, OS, SM Baloga, and LS Glaze, 2004, "Comparing landslides to fluidized crater ejecta on Mars, JGR (accepted); Fagents, SA and SM Baloga, 2003, "Calculation of lahar transit times using digital elevation data", JVGR (to appear); Glaze, LS and SM Baloga, 2003, "DEM Flow path prediction algorithm for geologic mass movements," Env and Eng Geoscience (to appear Nov 2003) Glaze, LS, Baloga, SM and OS Barnouin-Jha, 2002, "Rheologic inferences from high water marks of debris flows, Geophys Res Letts 29, No 0, 10.1029/2002GL014757

This topical area has had a host of publications on a variety of different subjects including both terrestrial and planetary applications. However, there has been the common theme of developing a mathematical model, then obtaining field data to estimate the parameters, and finally to transfer the knowledge gained to a better understanding of similar processes on the planetary surfaces.

5. Io Plumes and Auras

Primary Publications: Glaze and Baloga, 2000, "Stochastic-ballistic plumes on Io", JGR/Planets, 105, E7 17,579-588; LPSC 2001: Baloga and Glaze, "Potential mechanisms for the formation of lava flow auras on Io"

In Glaze and Baloga [2000], we developed the stochastic-ballistic theory for volcanic plumes on Io and applied it to the bright annular deposit at Prometheus. The stochastic region is considered to be a hemisphere near the vent with a radius that is small compared to the overall dimensions of the plume. Within this region, the random effects associated with collisions of particles, thermalization, irregularities in vent conditions, and perhaps phase changes, dominate the dynamics. The theory assumes that the important transport variables (e.g., energy, momentum, ejection angles) have probability distributions. Once particles leave the stochastic region, the randomizing influences on particle motions cease and the subsequent trajectories are purely ballistic. In the Prometheus application, it was found that a narrow Gaussian exit energy distribution (RSD=8%) and a modestly truncated ejection cone (75° from the vertical) are required to produce an annulus similar in size and shape to the image data. Only small changes in the nature of the energy distribution, dispersion, and angular ejection distributions were found to be admissible if the annulus is to be preserved.

We also used the constraint on the energetics to determine admissible compositions of the annulus. Plume temperatures at the vent were chosen to be representative of three plausible styles of volcanism (sulfur, basaltic, and ultramafic). For each style of volcanism, it was found that only a limited range of atomic weights (32-64 for sulfur volcanism, 64-128 for basaltic volcanism, and compositions in a range greater than 64 and less than 256 for ultramafic volcanism) were permitted by the size and brightness distribution of the Prometheus annulus.

Bright deposits on Io. This research focused on the bright annular deposits volcanic plumes and the bright conforming margins of lava flows, known as “auras”. During the last year, our manuscript on volcanic plumes on Io appeared [Glaze and Baloga, 2000, “Stochastic-ballistic plumes on Io”, JGR/Planets, 105, E7 17,579-588]. This work presented a theory for volcanic plumes on Io and applied it to the bright cylindrically symmetric annular deposit at Prometheus. The stochastic-ballistic model divides a plume into a small region near the vent, where random effects occur, and a larger region where the transport of plume particles is purely ballistic. For data/theory comparisons we have assumed that the brightness observed in imaging data is proportional to the areal concentration of plume particles. This theory was found to provide very good agreement with the profiles at Prometheus, provide plausible compositional constraints, and explain why annuli are observed for some eruptions, but not others.

Since the publication of the plume paper, we have focused on adapting the theory for the auras at Talos Patera. Three plausible alternative hypotheses for the formation of auras were investigated. **Hypothesis 1:** Heat from the flow releases volatiles from the regolith beside the flow. The volatiles are then transported above the surface and deposited to form the aura. **Hypothesis 2:** Volatiles are derived directly from the surface of the flow itself. Once liberated, they follow ballistic trajectories to the surface. **Hypothesis 3:** Heat from the fresh lava flow propagates through the regolith, locally mobilizing the volatiles throughout the entire lateral extent of the aura, where they condense immediately at the surface. We have reformulated the stochastic-ballistic model so that it can be applied to the auras. We have also developed compositional constraints by assuming 3 different styles of volcanism for the flow itself: basalt, ultramafic, and sulphur. Results of this analysis were reported at the recent LPSC [Baloga and Glaze, 2001, Potential mechanisms for the formation of

lava flow auras on Io, Abstract, LPSC XXXII].

6. PUBLICATIONS AND ABSTRACTS FROM GRANT:

SELECTED RESEARCH PUBLICATIONS:

Baloga SM, PJ Mouginis-Mark, and SA Fagents, 2004, The formation of Martian rampart craters" (Submitted to JGR Planets); **Mouginis-Mark, PJ, H Garbeil, JM Boyce, CSE Ui, and SM Baloga**, 2004, "Geometry of Martian Impact Craters: First results from an interactive software package", JGR Planets (accepted); **Non-Random Processes Control Clustering within Rootless Cone Groups on Iceland and Mars** B. C. Bruno, S. A. Fagents, T. Thordarson, S. M. Baloga and E. Pilger ; **Barnouin-Ja, OS, SM Baloga, and LS Glaze**, 2004, "Comparing landslides to fluidized crater ejecta on Mars, JGR (accepted), **Baloga, SM, PJ Mouginis-Mark, and LS Glaze**, 2003, "The rheology of a long lava flow at Pavonis Mons", JGR/Planets (108, E7,5066, doi 10:1029/2002JE001981); **LS Glaze, SM Baloga, and ER Stofan**, 2003, "A methodology for constraining lava flow rheologies with MOLA", Icarus (doi:10.1016/A0019-1035(03)00171-4) **Baloga, SM and LS Glaze**, 2003, "Pahoehoe transport as a correlated random walk", JGR Solid Earth 108: 10.1029/2001JB001739; **Fagents, SA and SM Baloga**, 2003, "Calculation of lahar transit times using digital elevation data", JVGR (to appear); **Glaze, LS and SM Baloga**, 2003, "DEM Flow path prediction algorithm for geologic mass movements," Env and Eng Geoscience, IX, 3, 225-240; **Glaze LS and SM Baloga**, 2002, "Volcanic plume heights on Mars: Limits of validity for convective models, JGR Planets, 10.1029/ 2001JE001830; **LS Glaze, ER Stofan, S Smrekar, and SM Baloga**, 2002, "Insights into coronae formation through statistical analysis" JGR Planets 107, E12, Paper 18; **Glaze, LS, Baloga, SM and OS Barnouin-Jha**, 2002, Rheologic inferences from high water marks of debris flows, Geophys Res Letts 29, No 0, 10.1029/2002GL014757; **SM Baloga, LS Glaze, MN Peitersen, and JA Crisp**, 2001, "The influence of volatile loss on the thickness and density profiles of active basaltic flow lobes", JGR, 106, B7 13,395-13,405; **Glaze and Baloga**, 2000, "Stochastic-ballistic plumes on Io" JGR/Planets, 105,E7, 17,579-588; **Lang, HR and SM Baloga**, 2000, "Validation of airborne visible-infrared imaging spectrometer (AVIRIS) data at Ray Mine, AZ", GSA Env and Eng Geosciences, 3: 187-200; **Crown, DA and SM Baloga**, 1999, "Pahoehoe toe dimensions, morphology, and branching relationships at Mauna Ulu, Kilauea volcano, Hawaii", Bull. Volc, 61:288-305; **Glaze, LS and SM Baloga**, 1998, "Dimensions of Puu Oo lava flows on Mars", JGR/Planets, 103, 13,659-13,666; **Baloga, S, LS Glaze, JA Crisp, and SA Stockman**, 1998, "New statistics for estimating the bulk rheology of active lava flows: Puu Oo examples", JGR/ Solid Earth 103, 5133-5142;

SOME RECENT ABSTRACTS

LPSC (2003) Baloga, SM, LS Glaze, DA Crown, Scaling of Pahoehoe Flow Field Features. Paper # 1437; Barnouin-Jha, OS and S Baloga, Comparing Run-Out Efficiency of Fluidized Ejecta on Mars with Terrestrial and Martian Mass Movements. Paper # 1599; Glaze, LS, SM Baloga, ER Stofan, PJ Mouginis-Mark, KM Shockey and S McColley, Rheology Comparisons for Several Martian and Terrestrial Lava Flows. Paper # 1315; Anderson, SW, L Glaze, E Stofan and S Baloga, The Spatial Distribution of Lava Flow surface features on Earth and Mars. Paper # 1080; Fagents, SA and SM

Baloga, Simulations of Lahar Emplacement on Earth and Mars. Paper # 1788; Mougini-Mark, PJ, H Garbeil, JM Boyce, SM Baloga, and C Ui, Measurements of Martian Impact Crater Geometry Via a New Interactive Computer Program. Paper # 1472; Stofan, ER, LS Glaze, SE Smrekar and SM Baloga, A Statistical Analysis of Corona Topography: New Insights into Corona Formation and Evolution. Paper # 1594. **LPSC (2002)**: SM Baloga, LS Glaze, JA Crisp, Channelized lava flows with density changes during emplacement; Glaze et al., MOLA constraints on lava flow rheologies. **AGU (2001)**: SM Baloga, PJ Mougini-Mark, LS Glaze, Massive debris flows at Pavonis and Arsia Montes, Mars; LS Glaze, SM Baloga, ER Stofan and S McColley, New Constraints on Martian Lava Flow Rheologies From MOLA. **GSA (2001)**: J.R. Zimbelman, Lori S. Glaze, Stephen M. Baloga, and Miyamoto Hideaki, Comparison of finite difference method and computational calculus approaches in simulating lava flow paths on Mars. **LPSC 2001**: Baloga and Glaze, Potential mechanisms for the formation of lava flow auras on Io; Glaze and Baloga, Validity of convective plume rise models for volcanic eruptions on Mars; PD Spudis and S Baloga, Mixing of the mare regolith: A Clementine test; Stofan et al., An updated database of coronae on Venus. **LPSC 2000**: SM Baloga and LS Glaze, Pahoehoe transport as a correlated random walk; MN Peitersen, SM Baloga, LS Glaze, JA Crisp, The influence of degassing on the lava flows: Implications for planetary modeling studies; LS Glaze and SM Baloga, Stochastic-ballistic plumes on Io: Sensitivity of deposition to high ejection angles; **LPSC 1999**: LS Glaze and SM Baloga, Application of a stochastic-ballistic emplacement model for Io plume deposits; DACrown, SM Baloga, JM Byrnes, Emplacement of pahoehoe flow fields: scale-dependent characteristics of Mauna Ulu flows; JB Garvin and SM Baloga, Inferences on the emplacement dynamics of martian impact crater ejecta: constraints from MOLA topography. **LPSC 1998**: DACrown, JM Byrnes, SM Baloga, Scale-dependent characteristics of Mauna Ulu pahoehoe flows. LS Glaze, SM Baloga, PJ Mougini-Mark, An unusual lava flow emplacement process at Elysium Planitia, Mars. **LPSC 1997** LS Glaze, SM Baloga, SA Stockman, JA Crisp, Simulations of Puu Oo lava flows on Mars.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE July 31, 2004	3. REPORT TYPE AND DATES COVERED 5/1/01 thru 4/30/04 FINAL REPORT		
4. TITLE AND SUBTITLE Quarterly Progress Report #E04-001		5. FUNDING NUMBERS		
6. AUTHORS Stephen M. Baloga		NAG-10530		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Proxemy Research 20528 Farcroft Lane Laytonsville, MD 20882		8. PERFORMING ORGANIZATION REPORT NUMBER E04-001		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) NASA Code SE Washington, DC 20546		10. SPONSORING/MONITORING AGENCY REPORT NUMBER		
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT		12b. DISTRIBUTION CODE		
13. ABSTRACT (Maximum 200 words) Proxemy Research has a research grant to perform scientific investigations of volcanism and volcanic-related process on other planets. Part of this research involves mathematical modeling of specific volcanic transport processes and the use of terrestrial analogs. This report is submitted in accordance with grant NAG-10530 and contains a summary of activities conducted over the time period indicated in field 3, above. In addition, a synopsis of science research conducted during the period is given. A complete listing of publications and scientific abstracts that were presented at scientific conferences is contained in the report.				
14. SUBJECT TERMS EOS VolcIDS			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT SAR	